Solar and Stellar Winds

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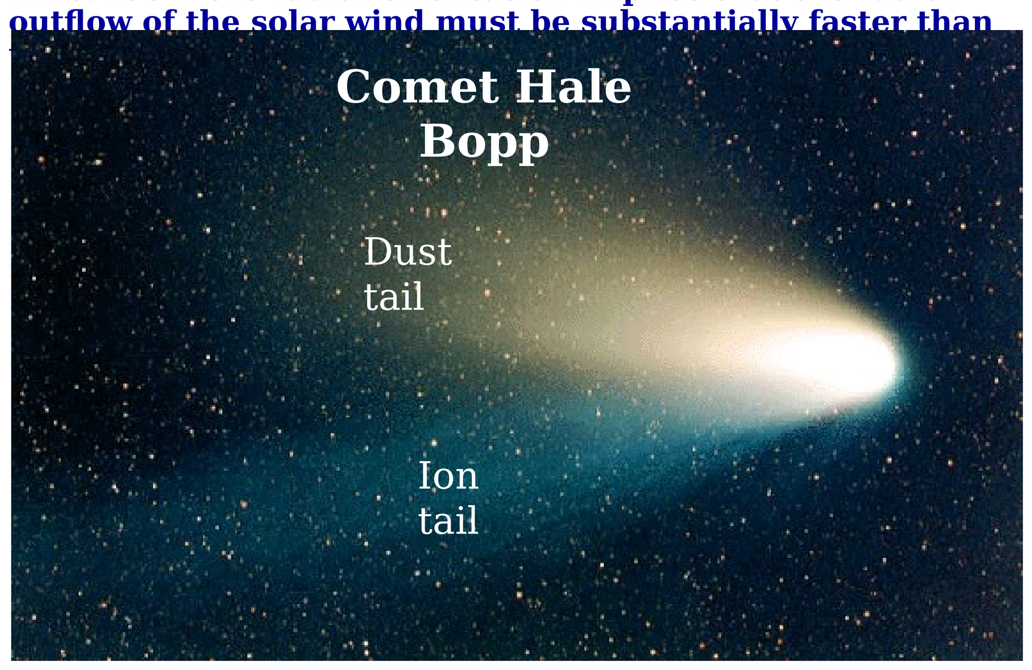
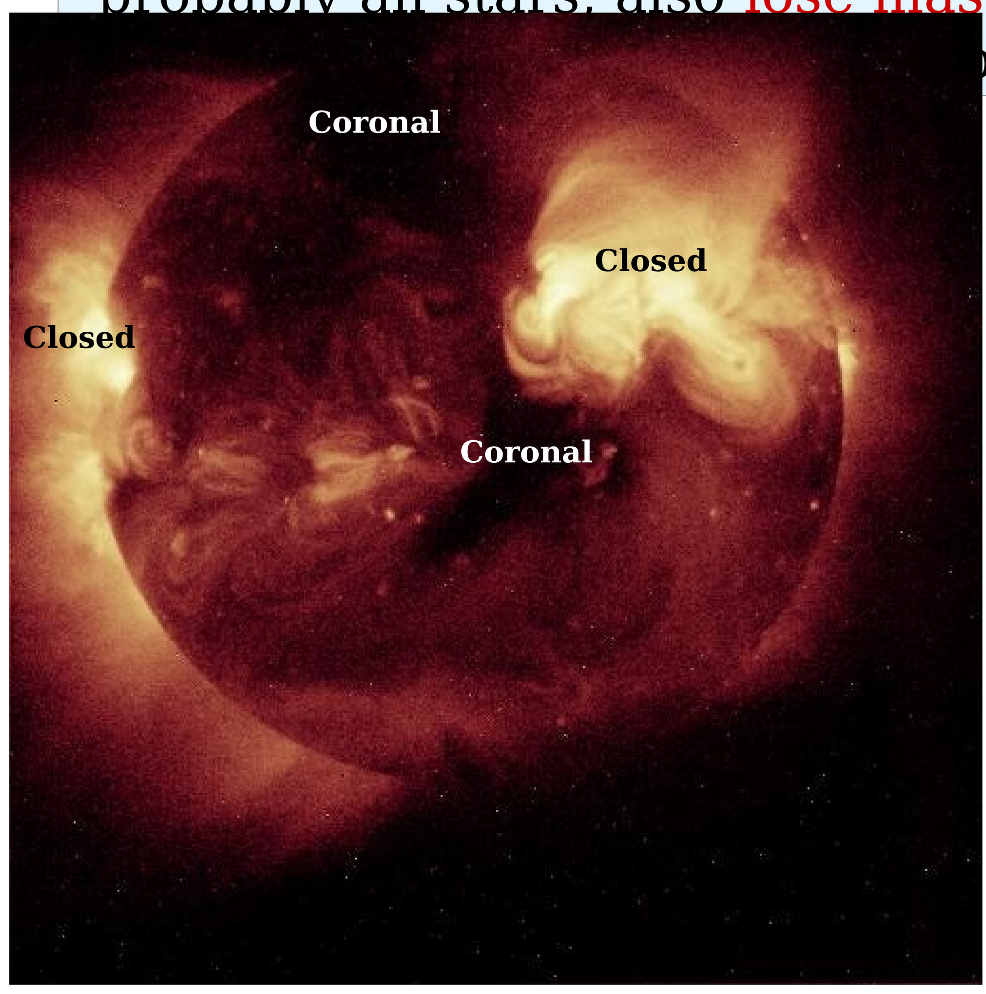
The Sun and other stars are commonly characterized by the radiation they emit.
But the past half-century has seen the discovery that the sun, and probably all stars, also lose mass through an essentially continuous, outflow or "wind".

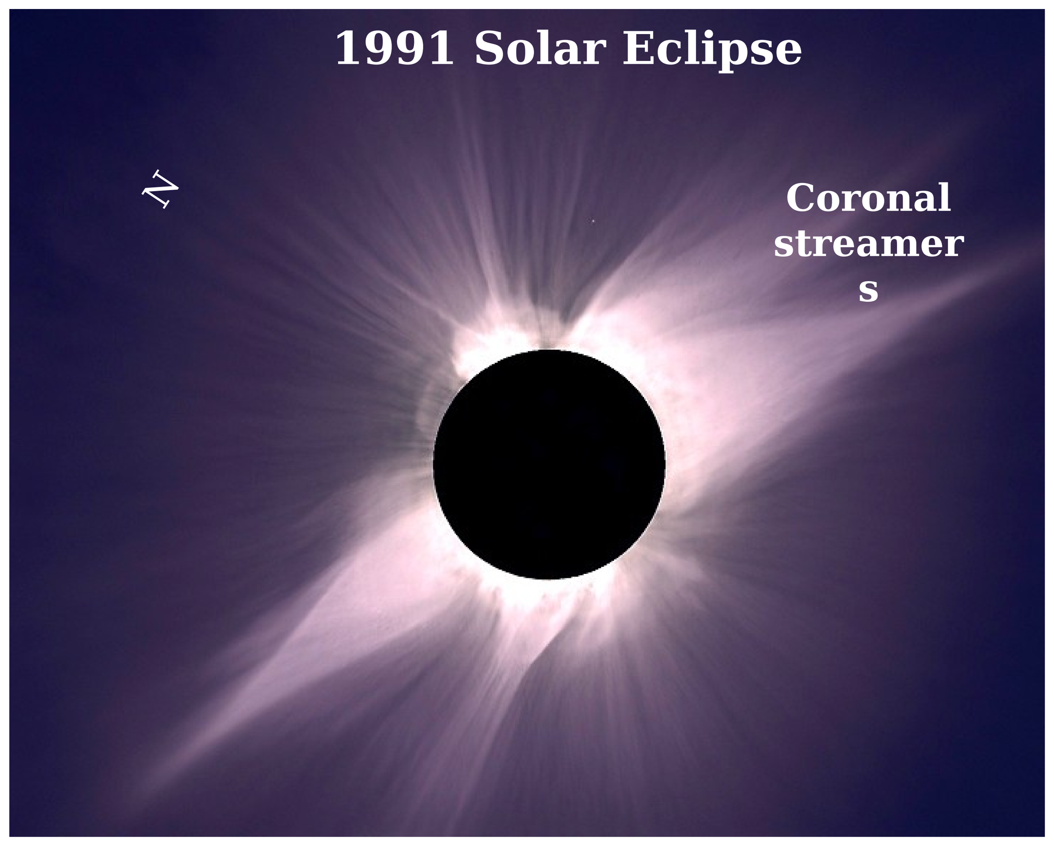
The Solar Wind

- Early evidence that the sun might be continuously expelling plasma at a high speed came from observations of the dual tails of comets.
- One tail, made of dust slowly driven away from the comet by solar radiation, has an orientation that is tilted to the anti-sun (radial) direction by the comet's own orbital motion.
- A second tail comes from cometary ions picked by the solar wind. It's more radial orientation implies that the radial outflow of the solar wind must be substantially faster than

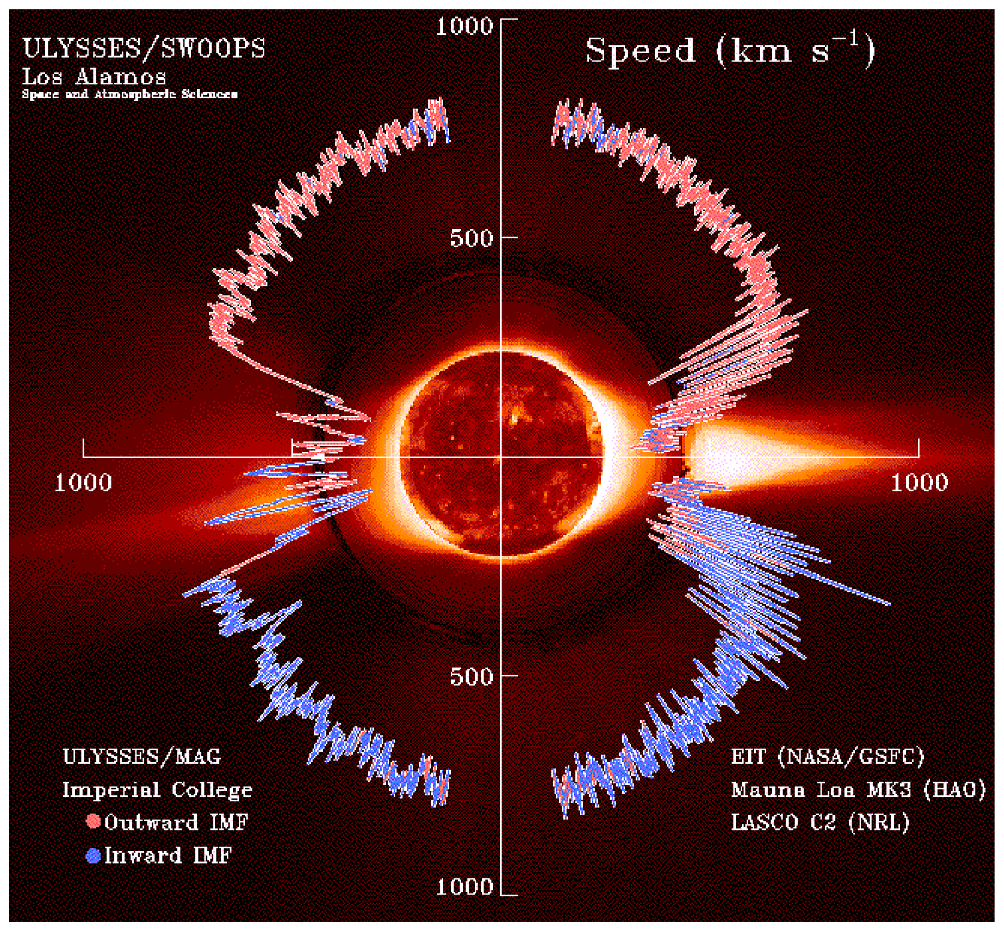


- The cause of the solar wind is the pressure expansion of the very hot (million degrees Kelvin) solar corona.
- The high temperature causes the corona to emit X-rays.
- Images made by orbiting X-ray telescopes show the solar corona has a high degree of spatial structure, organized by magnetic fields. Within closed field coronal loops, these effectively hold back the coronal expansion. But along radially oriented, open-field regions the wind flows rapidly outward, leading to a relative reduction of the plasma density that appears as a relatively dark "coronal hole".

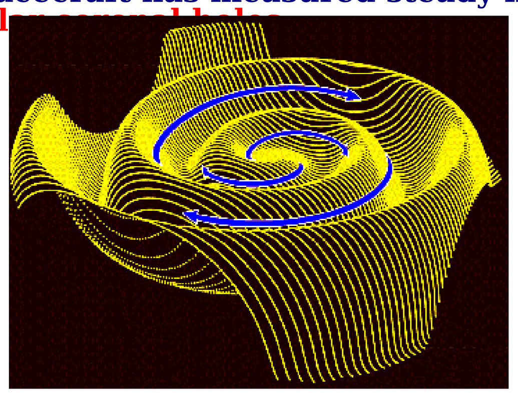




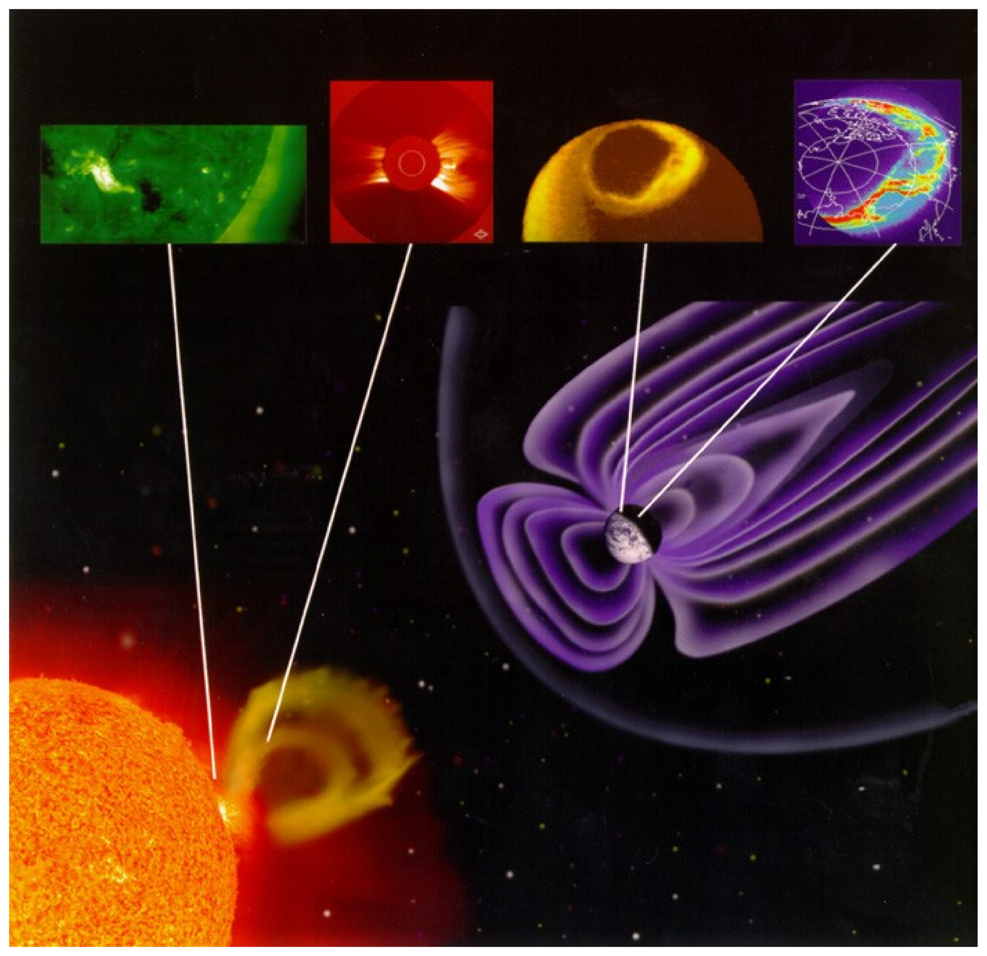
- The corona can also be observed in white light from the ground during a solar eclipse, or using "coronagraphs" with occulting disks that artificially eclipse the bright solar disk.
- Such images show the closed loops are extended outward into radial coronal streamers by the wind outflow.
- Both X-ray and white-light observations show that closed-field loops tend to occur near the equator, while open-field coronal holes are usually near the solar poles.
- But the solar wind is most directly observed *in situ* by interplanetary spacecraft with plasma instruments to measure the wind's speed, elemental composition, ionization state, and the interplanetary magnetic field (IMF).



- Coordinated interplanetary and coronal observations have demonstrated that coronal holes are the source of wind streams with a much higher speed (>700 km/s) than the typical, slower (~400 km/s) wind.
- As first to fly far out of the ecliptic plane, the *Ulysses* spacecraft has measured steady high-speed wind from polar coronal holes.

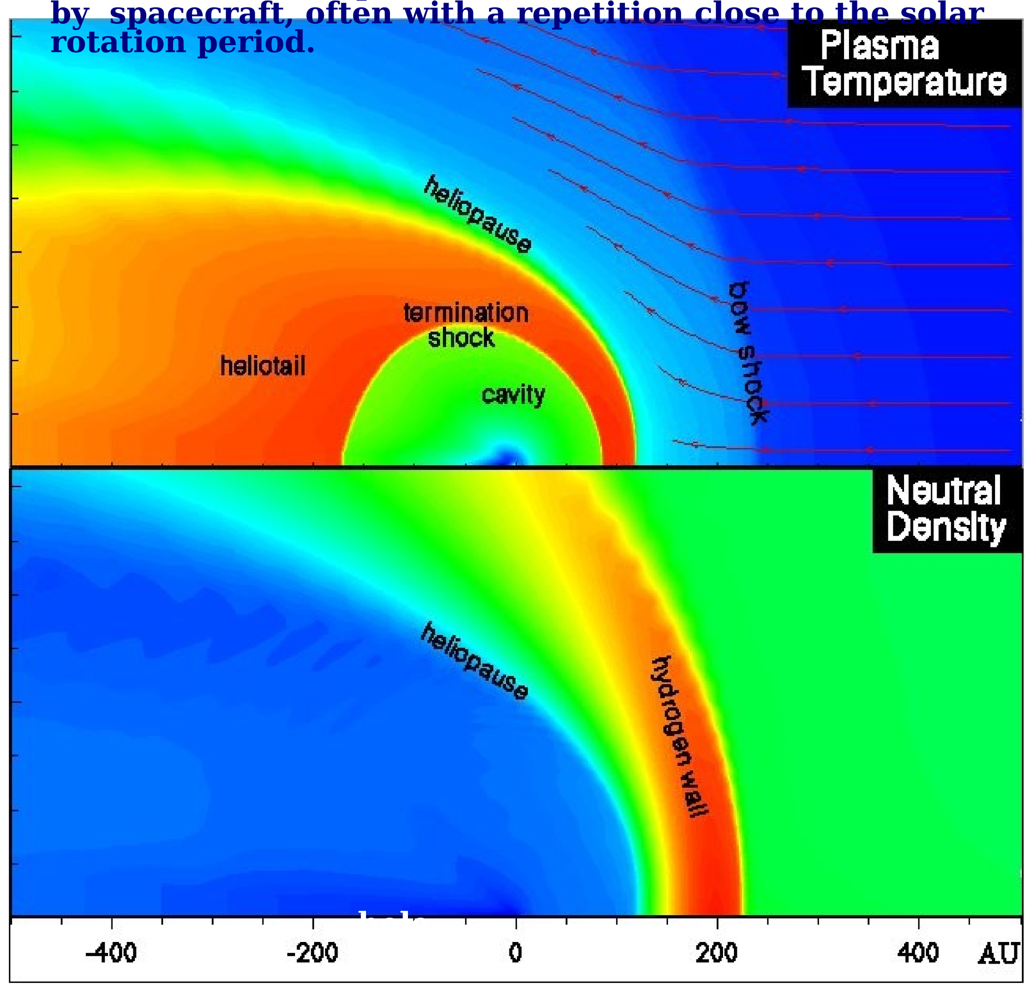


- At high latitudes the IMF has a nearly uniform polarity set by its coronal source region.
- But near the ecliptic it can repeatedly switch as the spacecraft crosses a warped, spiral current sheet surface.



- The solar wind interacts with the earth's magnetosphere, providing a key way that solar activity can induce geomagnetic activity, and perhaps even influence earth's climate and weather.
- Finally, the solar wind blows out a "heliospheric cavity" in the local interstellar medium. The Voyager spacecraft may reach the "bow shock" of this cavity within the next couple decades.

- The generally lower-speed ecliptic-plane wind also shows abrupt switches to high-speed streams that originate from low-latitude coronal holes.
- The rotation of the sun brings about a collision between these high- and low-speed streams along spiral Co-rotating Interaction Regions, forming abrupt shock discontinuities in plasma conditions that are measured by spacecraft, often with a repetition close to the solar rotation period.

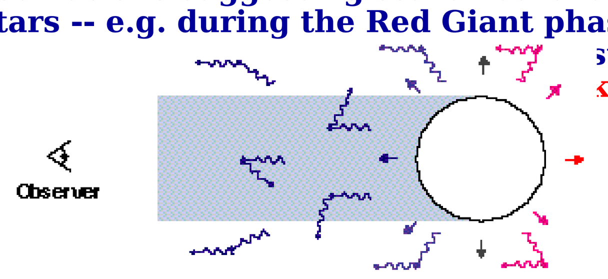


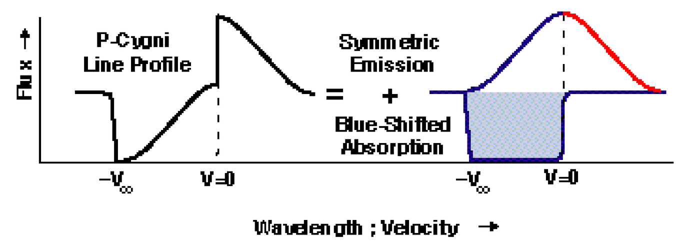
loops

loops

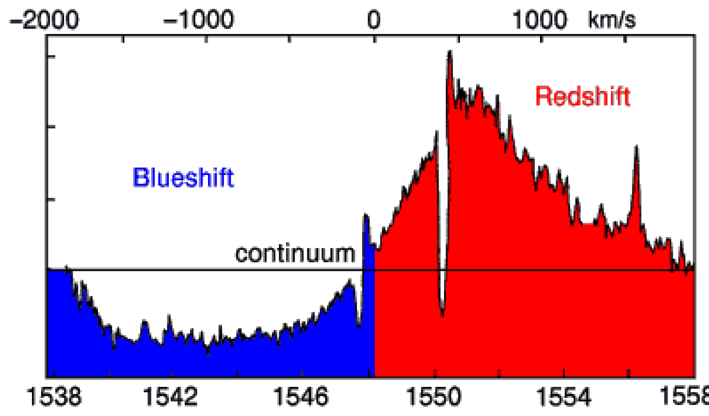
Stellar Winds

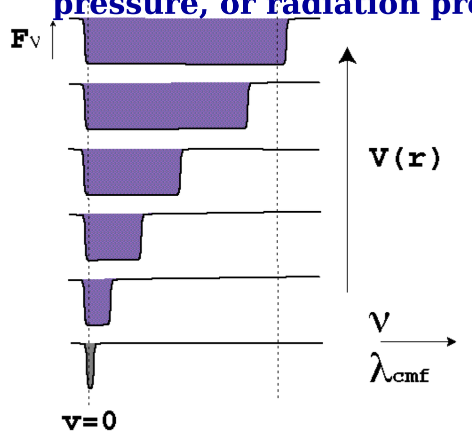
- Evidence of episodic stellar mass loss in the form of novae or supernovae has been known since antiquity. But the realization that stars could also have a continuous wind dates from the 1960's, largely from analogy with the solar wind.
- Low-density, optically thin coronal winds from solar-like, low mass, main-sequence stars can only be inferred indirectly, e.g. by X-ray observations suggesting stellar coronae.
- But for some stars -- e.g. during the Red Giant phase of a solar-mass ... stars -- the stellar win... in spectral lin...

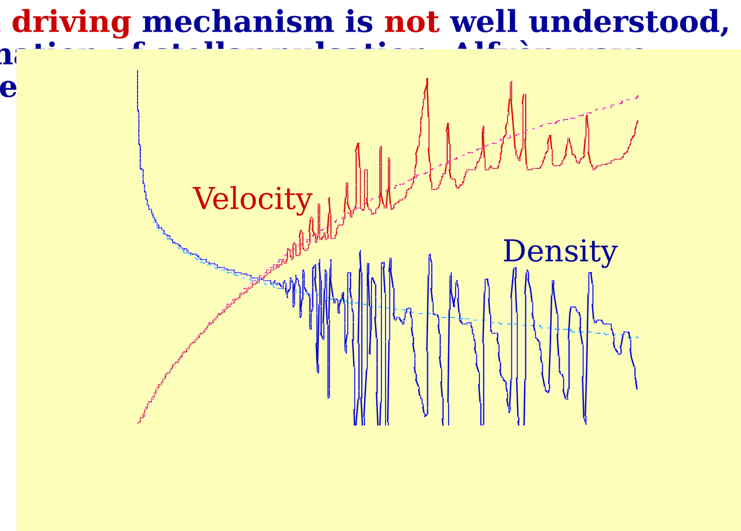




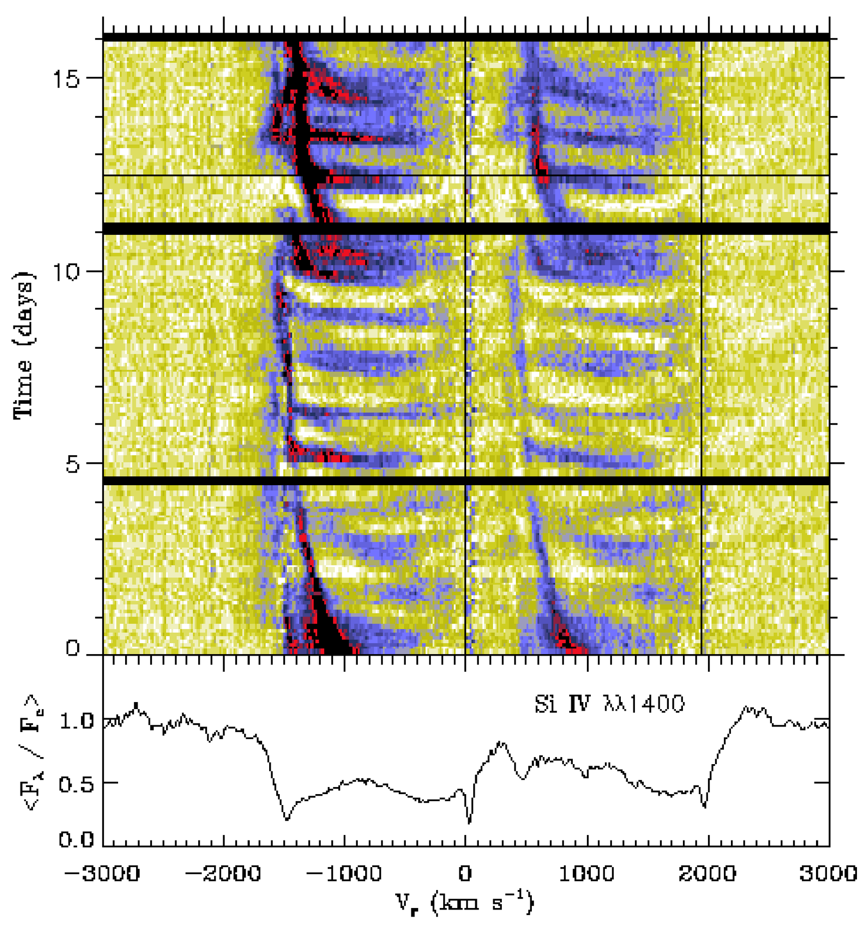
- Line formation by scattering of the stellar radiation within the expanding wind develop a characteristic shape -- a P-Cygni profile -- whose features provide a direct diagnostic of key wind parameters, like the wind speed and mass loss rate .
- For Red Giant stars, such profiles suggest relatively slow speeds, 10-50 km/s, but with mass loss rates up to million times that of the solar wind, i.e., ~ 10^{-8} $M_\odot$/yr.
- But massive stars show the strongest winds, with speeds sometimes exceeding 3000 km/s, and mass loss rates up to a billion times the solar wind, i.e. ~ 10^{-5} $M_\odot$/yr !
- This is large enough that, during the course of their relatively brief (~10^7 yr) evolutionary lifetime, such massive stars can be stripped of their entire hydrogen envelope, exposing a "Wolf-Rayet" star characterized by strong line emission from ions of nuclear processed elements like Carbon, Nitrogen, and Oxygen.
- For Red Giants the wind driving mechanism is not well understood, but may involve a combination of ... pressure, or radiation pre...



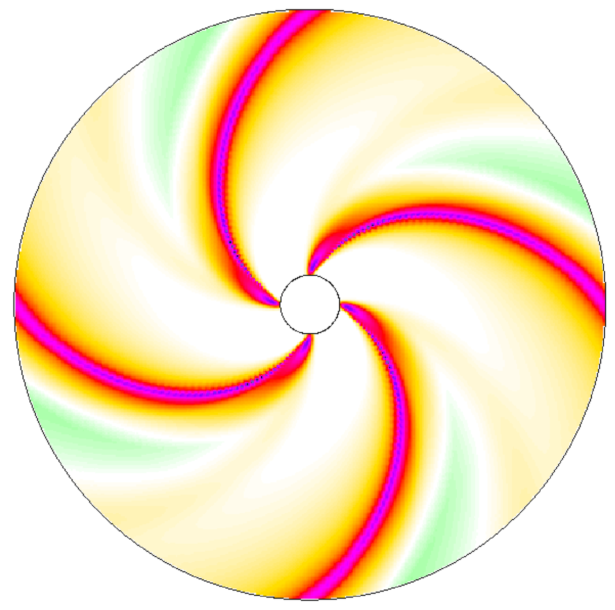


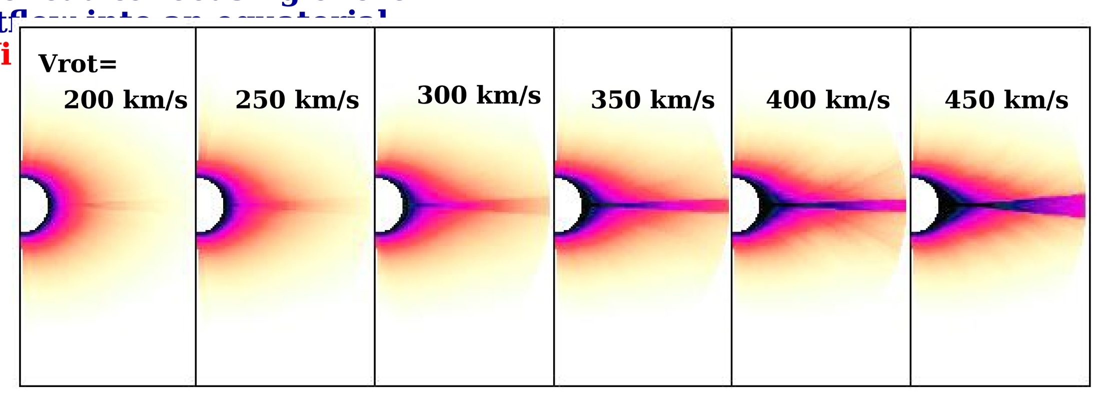


- For hot, luminous stars the driving is generally thought to stem from radiation pressure acting through line scattering. The Doppler shift of the line-profile within the expanding wind effectively "sweeps out" the star's continuum momentum flux.
- This makes the driving force a function of the wind velocity and acceleration, leading to strong instabilities that likely make such winds highly turbulent.



- Monitoring campaigns of P-Cygni lines formed in hot-star winds also often show modulation at periods comparable to the stellar rotation period.
- These may stem from large-scale surface structure that induces spiral wind variation analogous to solar Corotating Interaction Regions.
- The generally rapid rotation of hot stars can also lead to focusing of the outflow into an equatorial "Wi...



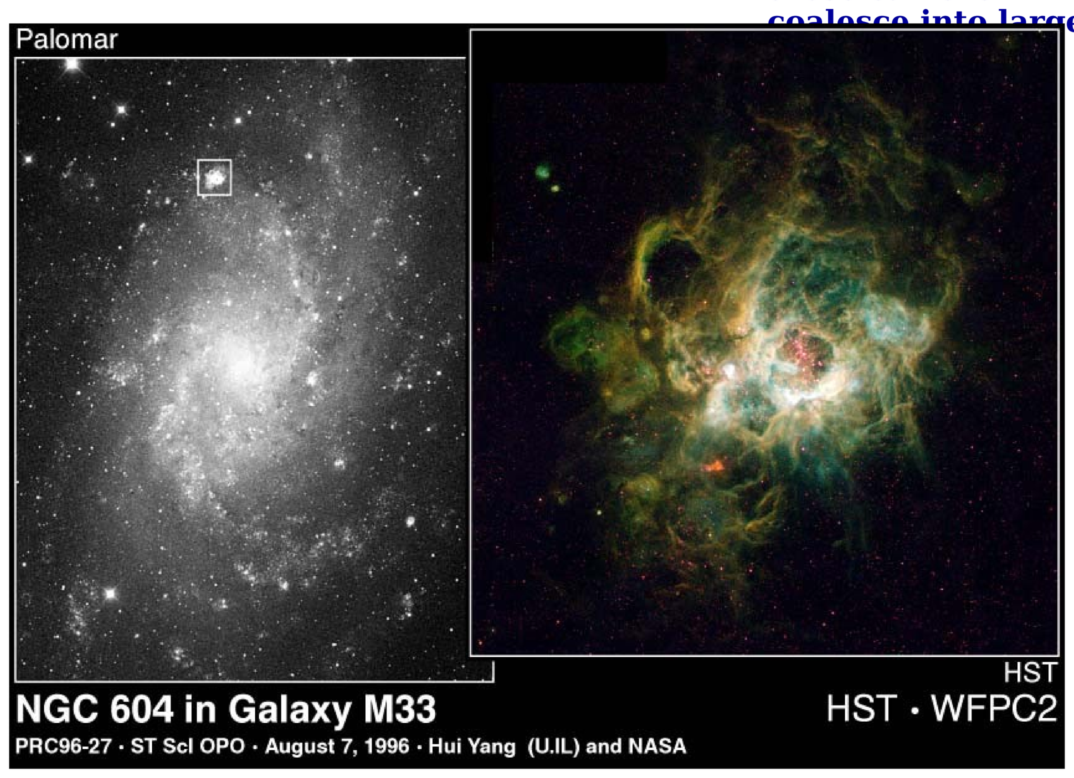


WR wind bubble NGC 2359

- The large mass loss of hot-stars also represents a substantial source of energy and mass into the interstellar medium.
- Indeed, interstellar nebulae near young star clusters often show clear "wind-blown bubbles" from the many hot, massive stars.
- In particularly dense clusters, these can even coalesce into large

Superbubble in the Large Magellanic Cloud

- The compression around such wind bubbles may play a role in triggering further star formation. Some galaxies even appear to be undergoing "starbursts", with integrated spectra dominated by young, massive stars.
- Radiative driving processes similar to those occurring in hot-star winds may even be key to understanding broad-line outflows from Active Galac...



NGC 604 in Galaxy M33

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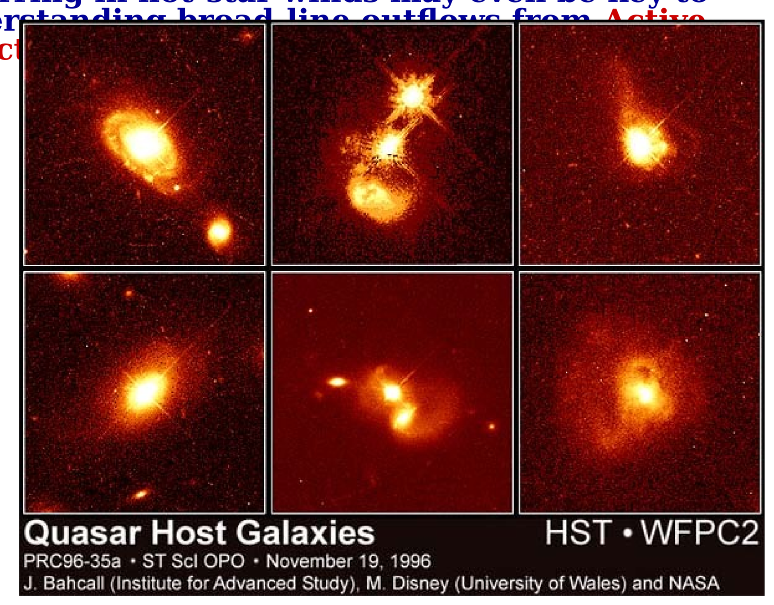

Quasar Host Galaxies

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